ON THE NEEDS, REQUIREMENTS AND FEASIBILITY OF A SPACE-BORNE WIND PROFILER

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ABSTRACT

The skill of current NWP models relies much on the availability of meteorological observations. Because NWP models have improved much over the last decades and advanced 4-dimensional variational techniques are now being used for the analysis, a need for information on the sub-synoptic scales becomes apparent for a further improvement of NWP. On these scales the atmospheric dynamics are determined by the wind field, rather than the atmospheric temperature field. Furthermore, the prime factor determining meteorological instability is vertical wind-shear. In the tropics, for an accurate definition of the Hadley circulation, 3-dimensional wind information has been lacking. Conventional wind profile data lack coverage and uniform distribution over the globe. Thus, we need wind profilers in order to improve the meteorological Global Observing System. For this purpose, there are efforts worldwide to provide independent observations of the atmospheric wind field. The US started with a Doppler wind lidar (DWL) programme drawing on the LAWS (laser atmospheric wind sounder) concept. Japan has plans for JLAWS (Japanese LAWS). In Europe, the European Space Agency (ESA) is, in the context of the Earth Explorers, preparing a mission aiming at the observation of the atmospheric wind field, namely the Atmospheric Dynamics Mission (ADM). Its main component will be a DWL called ALADIN.

On the requirement side, WMO has defined requirements on data quality for wind profile measurements and these have been further refined in the context of the ADM. Several technological options exist for the realisation of a DWL, but each with different performances and costs. This document will present a review on the overall needs as well as the different levels of requirements identified and the implementation possibilities.

1. The Need

Continuous measurements of winds throughout the atmosphere are crucial for both Numerical Weather Prediction (NWP) and an increasing range of studies related to the global climate, its variability, predictability and change. Reliable instantaneous analyses and longer-term climatologies of winds are needed to improve our understanding of atmospheric dynamics and the global atmospheric transport and cycling of energy, water, aerosols, chemicals and other airborne materials. This requires observation of winds at all levels in the lower atmosphere (primarily troposphere and stratosphere) and at the Earth's surface. There is a need to get better wind observations for NWP and climate research at the earliest possible date.

While meteorological observations have been carried out from space for several decades, direct measurements of the global, three-dimensional wind field are still outstanding. Deficiencies in the current observing system, including coverage and frequency of observations, are impeding progress in both operational weather forecasting and climate-related studies. Furthermore, there is now a tendency to reduce the number of conventional observation sites (e.g. radiosonde stations) primarily for cost reasons. In contrast, improvements in the available wind data are needed urgently to exploit the full potential of recent advances in NWP (e.g. 4-dimensional variational assimilation - 4DVAR).

1.1 Numerical Weather Prediction (NWP)

At present, the information on the wind field over the oceans, the tropics and the Southern Hemisphere is derived applying indirect methods. It is severely limited by having to rely mainly on space-borne observations of the mass field, and quasi-geostrophic adjustment processes (cf ESA, 1996). A Doppler wind lidar (DWL) has the potential to provide the requisite data by means of direct observations in clear air (i.e. above cloud in case of overcast conditions) globally. In addition, a DWL would also provide much needed ancillary information as e.g. cloud top heights or aerosol distribution. Vertical wind shear is an important cause of air turbulence. Mid-latitude weather systems are believed to have their origin in processes encapsulated in the theory of baroclinic instability. A suitable measure of baroclinicity is provided by the Eady growth rate depending on vertical wind shear and horizontal gradients of temperature and humidity (cf Hoskins et al., 1978). In the free troposphere mainly variations in the vertical wind shear, rather than horizontal gradients of temperature and humidity, determine the instability (Stoffelen and Marseille, 1998, for a more detailed discussion). As such, wind profile data is expected to deliver important precursor information for cyclone development.

1.2 Climate

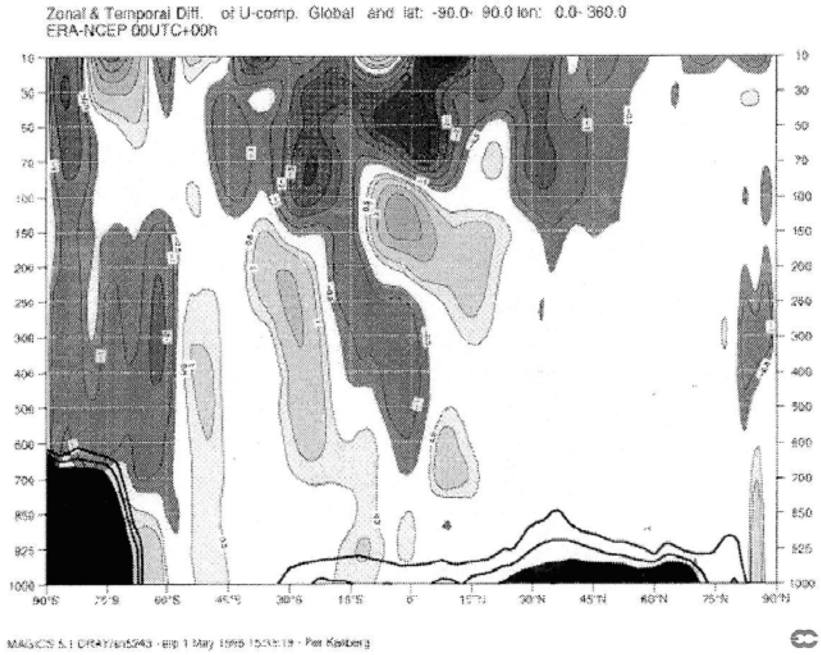

Figure 1: *Differences of the zonal wind components in ERA and NCEP re-analysis for 7 July 1987. Major uncertainty exists in the atmosphere's dynamics in the tropics and in the Southern hemisphere.*

There is a strong relationship between advances in NWP and those in climate-related studies. Climate studies are increasingly using analyses of atmospheric (and other) fields from data assimilation systems designed originally to provide initial conditions for operational weather forecasting models. The understanding of the atmosphere and its evolution is based to a large extent on the analysed fields from continuous data assimilation carried out at operational weather centres, so that progress in climate analysis is linked closely to corresponding progress in NWP. Reanalysis over extended periods are being carried out at NCEP (Kalnay et al., 1996) and ECMWF (Gibson et al., 1997).

From the results it is apparent that the variability introduced by atmospheric disturbances proves important for longer term processes in climate. Substantial uncertainty exists in the definition of the atmospheric flow. The uncertainties in modeling and observation are illustrated in Figure 1.

In the context of climate studies, the need for better global wind profile measurements has been expressed as one of the highest priority concerns by the World Climate Research Programme (WCRP) with the Global Energy and Water Cycle Experiment (GEWEX) as a major component.

1.3 The Global Observing System (GOS)

In order to obtain a description of the atmosphere, a composite observing system has been established. It consists of a number of different observing platforms which either take observations at pre-specified times (synoptic hours) or quasi continuously. They can be grouped further into in-situ measurements or remote-sensing data. They either provide information for one level only (surface or upper air) or give profiles for a number of levels in the vertical (a typical number of global observations is shown in Figure 2).

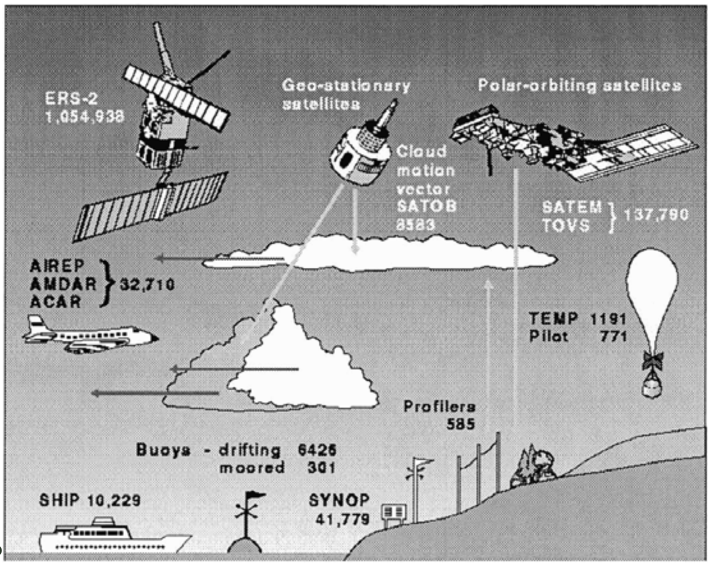

Figure 2: *Example of a 24 hour summary of global data volumes for all observation types received at ECMWF (here: 26 April 1996).*

The present data deficiencies in NWP can be summarized as follows: the surface-based, conventional network shows large gaps in the Southern Hemisphere, in the tropics, and over the oceans in the Northern Hemisphere. Satellite soundings provide global coverage with radiance data, which can only be used indirectly for the definition of the mass field. Radiosondes and pilot balloons are the only observing systems providing vertical profiles of the wind field. They are available mainly from the continents in the Northern Hemisphere. Very little information about the vertical profile of the wind field is available from the oceans, in the tropics and in the Southern Hemisphere.

Cloud motion winds, most aircraft reports, surface stations and scatterometer winds are single level observations and these are more difficult to use than profile measurements because of the uncertainty of how to spread the information in the vertical.

1.4 Evidence

Observational System Experiments (OSE's) carried out by ECMWF (see Figure 3), the German weather service (Wergen, 1998) and at NCEP (Atlas, 1998) with the TEMP/PILOT wind profiler network verified the relevance of wind profile data for NWP. Over these varied data assimilation systems and periods it was found that

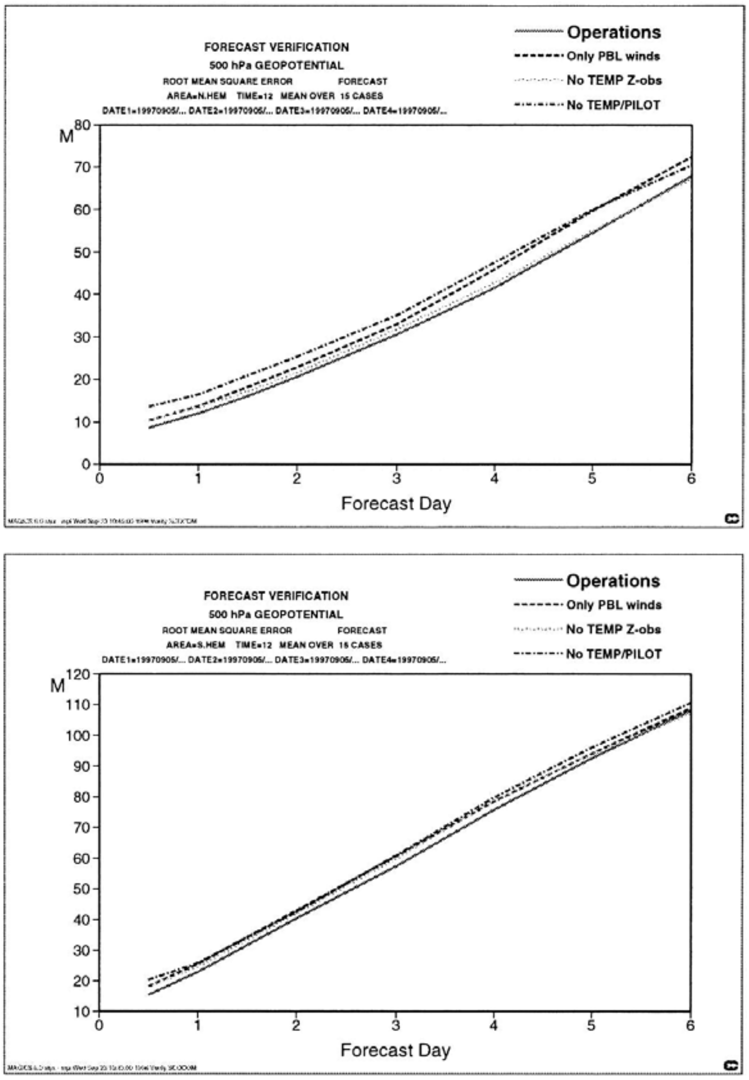

Figure 3: *Results of assimilation studies carried out with ECMWF's 3D-variational system for*

- *No use of TEMP/PILOT*
- *No use of TEMP/PILOTwinds above 775 hPa*
- *No use of TEMP/PILOT temperature profiles but only winds*

- though the wind profile network is relatively sparse and inhomogeneous, it provides the backbone for NWP;
- wind profile information in the PBL alone does not show much impact - the winds in the free troposphere and lower stratosphere are most relevant;
- TEMP temperature profile observation has relatively little impact as compared to wind profile data.

Observational System Simulator Experiments (OSSE's) have confirmed the importance of wind profile data (e.g. Pailleux et al., 1998 or Atlas, 1998). Since these experiments were low resolution and, sometimes, carried out with rather degraded systems, further OSSE work will be carried out with state-of-the-art data assimilations systems in order to further assess the potential of a DWL to improve analyses of the atmosphere.

1.5 Generic Requirements for Global Wind Observations

Driven by the recent evolution of NWP requirements a set of generic user requirements for global wind observations can be derived stemming from WMO (1996). For short to medium range weather forecasting the requirements are defined in Table 1. For the study of large-scale processes of the climate system similar requirements apply.

	PBL	Troposphere	Stratosphere
Vertical domain	0-2 km	2-16 km	16 - 20 km
Vertical resolution	< 0.1 km	< 0.5 km	< 2.0 km
Horizontal domain	global		
Horizontal resolution	< 100 km		
Accuracy (RMS component error)	< 1.5 m/s	< 1.5 m/s	< 2 m/s
Temporal sampling	< 3 hrs		

Table 1: *Generic Requirements for Operational Meteorology and NWP*

2. The Atmospheric Dynamics Mission

2.1 The Mission Objectives of the Atmospheric Dynamics Mission

The primary long-term objective of the Atmospheric Dynamics Mission (ADM) is to provide observations of profiles of the radial wind component. The usefulness of such observations has been shown in a series of assessment studies (e.g. Lorenc and Graham, 1992; Courtier et al., 1992). Further studies have addressed the generation of simulation tools to study the impact of Doppler Wind Lidar observations on numerical weather prediction (NWP) and climate modeling. One result was the creation of a data base for use in Observation System Simulation Experiments (OSSEs; Stoffelen et al., 1994). In addition, this mission will also provide aerosol and cloud top height observations similar to those of a backscatter lidar.

The ADM would also provide some of the data needed to address key concerns of the WCRP, i.e. quantification of climate variability, validation and improvement of climate models and process studies relevant to climate change. The establishment of a series of such missions (to ensure the continuity of the data supply) would help to realise some of the objectives of the Global Climate Observing System (GCOS).

2.2 The Observational Requirements for the Atmospheric Dynamics Mission

The observational requirements of the ADM (Table 2) correspond to a mission fully exploiting the technique. These would e.g. require global coverage, near-real-time data delivery and frequent revisits. Implementation would most probably require more than one DWL embarked on a free flying satellite designed in such a way that the observations can be exploited operationally.

	PBL	Troposphere	Stratosphere
Vertical Domain	0 - 2 km	2 - 16 km	16 - 20 km
Vertical Resolution	< 0.5 km	< 1.0 km	< 2.0 km
Horizontal Domain	Global		
Spatial Representation	< 50 km		
Temporal sampling	6 hrs		
Profile separation	> 200 km		
Accuracy	2 m/s	2 - 3 m/s	no requirement
Timeliness	near real-time		

Table 2: *Observational Requirements for Operational Meteorology and NWP*

Figure 4 presents the simulated coverage that is similar on the whole globe to TEMP/PILOT over the Northern hemisphere. Given the large impact of TEMP/PILOT observations demonstrated in OSE's and OSSE's great benefits can be expected from such a DWL on a global scale.

2.3 Feasibility of an Atmospheric Dynamics Mission

Within the frame of the European Space Agency's (ESA's) Living Planet Programme (ESA, 1998), for the post-2000 era two general classes of Earth Observation missions have been identified to address user requirements in Europe (ESA, 1995), namely:

- Earth Watch Missions - pre-operational missions;
- Earth Explorer Missions - research/demonstration missions.

Following an extensive consultative exercise nine missions were identified as potential candidates for Phase A study as Earth Explorer Core Missions. After assessment four were selected for actual study

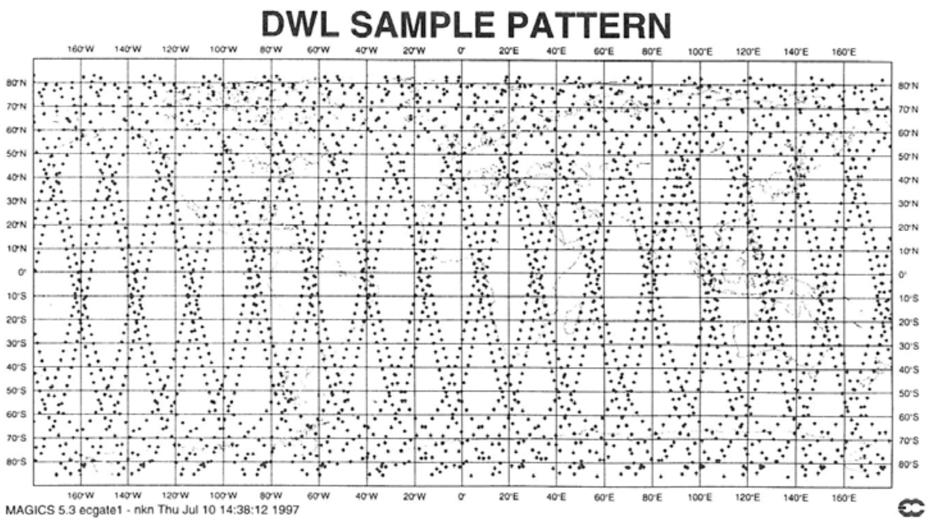

Figure 4: *Simulated coverage with a DWL on a polar orbiting satellite for a single day.*

including the Earth Explorer Atmospheric Dynamics Mission (ADM) (ESA, 1996). The core element of the Atmospheric Dynamics Mission is a DWL called ALADIN (atmospheric laser Doppler instrument) which can be used to provide accurate profiles of atmospheric wind. Furthermore, in areas of broken clouds, penetration below the cloud tops to clear air below will be possible (see Figure 5).

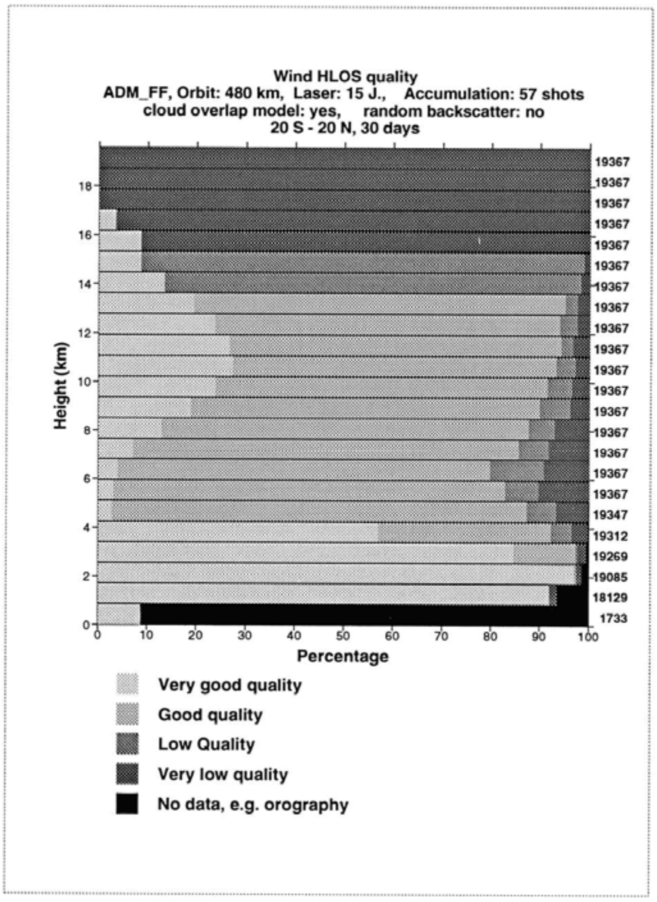

Figure 5: *Simulated performance of a DWL (energy: 15 J; 57 shots) on a polar orbiting satellite (ADM-FF = free flyer) for a period of one month for the tropics.*

Various instrument concepts have been studied at pre-Phase A level, leading to two designs based on carbon dioxide (CO_2) laser technology in the 10 µm wavelength range. These designs were originally tailored for use on a free flying satellite and included an attempt to optimise coverage with the aid of a scanning mechanism to achieve different lines-of-sight (LOS's). Advances in laser and detector technology have made it sensible to review some of the basic technical decisions including those of wavelength (from the ultraviolet up to 10 µm) and the detection technology (coherent versus direct detection).

Drawing on the results of scientific studies it was decided to give higher priority to the quality (i.e. accuracy and reliability) of the measurements as opposed to coverage. Such a mission would provide a good demonstration of the capabilities of such a system to meet the target mission objectives. Preference is, therefore, given to a design with one or two fixed LOS's but better signal characteristics, so limiting the complexity of both the instrument and the system (i.e. satellite). In the light of an assessment of the technological risks associated with this instrument the decision was made study the accommodation of a Doppler wind lidar on the International Space Station. The relevant trade-off's will be carried out during the Phase A study which has started in July 1998.

3. Conclusions

The US started with activities targeted at a DWL. The original concept was the LAWS (laser atmospheric wind sounder) concept. After refinement it is now planned to embark a DWL on a shuttle for technology demonstration in 2001. In the context of the IPO NPOESS programme there are also plans to embark an operational instrument in the 2007/8 time-frame. In Japan there are similar plans for a DWL called JLAWS (Japanese LAWS).

In the context of the European Space Agency's future Earth Observation *Living Planet Programme* (ESA, 1998) the Atmospheric Dynamics Mission is one of the four missions selected for further study. More detailed information on the context, the mission and its potential implementation can be found in ESA (1996) and Ingmann (1997). Depending on the observational requirements, quite a wide range of implementation scenarios can be considered. The target set of requirements is expected to be met by a constellation of free flyers. A DWL is planned to be embarked on the International Space Station in order to demonstrate the potential of accurate wind profile data for atmospheric dynamics analysis. After successful demonstration there are plans for a continuation ("wind watch") providing data for the operational meteorological community meeting the target requirements (see Table 2) in a time-frame similar to US plans.

Acknowledgement

The concepts presented in this document are very much relying on the results of on-going work within the Atmospheric Dynamics Mission Advisory Group, a Group of scientists advising the European Space Agency on the scientific aspects of the mission. The main target of their work is to define a concept which, while being scientifically attractive, at the same time, is technically feasible.

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